

OPTICAL DETECTION OF A VARIABLE MILLISECOND PULSAR COMPANION IN 47 TUCANAE¹

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ABSTRACT

Using results from radio and X-ray observations of millisecond pulsars in 47 Tucanae, and extensive *HST* *U*, *V*, *I* imaging of the globular cluster core, we have derived a common astrometric solution good to $< 0''.1$. A close positional coincidence is found for 47 Tuc U, a 4.3 ms pulsar in a 0.429 day orbit, detected in radio and X-rays, with an $m_V = 20.9$ blue star. Analysis of extensive time series data for this optical candidate shows a 0.004 magnitude semi-amplitude variation at the period and phase expected from the radio ephemeris, and the optical variations are spatially coincident with the candidate. This provides secure optical detection of the white dwarf companion to the millisecond pulsar, the first such detection in a globular cluster, allowing for comparisons to recent models for such companions with dependencies on mass and age.

Subject headings: binaries: general – globular clusters: individual (47 Tucanae) – pulsars: individual (PSR J0024–7203U) – pulsars: general

1. INTRODUCTION

The huge improvement in spatial resolution of *Chandra* over previous X-ray missions is proving, like *Hubble Space Telescope* (*HST*), to have significant impact on globular cluster astrophysics. For example, using *Chandra*, 108 sources have been detected in the central $2' \times 2'.5$ of the massive globular cluster 47 Tucanae (NGC104; Grindlay et al. 2001), compared to the detection of 9 central sources by *ROSAT* (Verbunt & Hasinger 1998). These *Chandra* sources are a mixture of millisecond pulsars (MSPs), cataclysmic variables (CVs), quiescent low-mass X-ray binaries, and active binaries, many of which have also been detected (Edmonds et al. 2001, in preparation) in our extensive 8.3 day *HST*/WFPC2 observations of this cluster (Gilliland et al. 2000). Fifteen of the 20 MSPs detected in 47 Tuc by Camilo et al. (2000) with the Parkes radio telescope have timing positions accurate to $\lesssim 0''.01$ (Freire et al. 2001; hereafter FCL01), and 10 of these are detected in X-rays with the CIAO program *wavdetect* (errors $\lesssim 0''.2$), allowing for excellent astrometry between the radio and X-ray coordinate frames. Combined with the large numbers of CVs and active binaries detected with both *Chandra* and *HST*, we exploit here the rare opportunity to perform astrometry at the $\sim 0.1''$ level between X-ray, optical, and radio observations, using only relative astrometry.

Of the 8 binary MSPs in 47 Tuc with timing solutions (FCL01), 5 have companions with masses of ~ 0.15 – $0.20 M_\odot$ (Camilo et al. 2000); by analogy with field MSPs these are expected to be helium white dwarfs (He WDs). Using our precise astrometry we report here the unam-

biguous detection of a He WD companion to one of these MSPs (PSR J0024–7203U, hereafter 47 Tuc U), the first such detection in a globular cluster. (He WDs have been reported in the globular cluster NGC 6397 by Cool et al. 1998, Edmonds et al. 1999, and Taylor et al. 2001, but none of these have yet been associated with an MSP.) The astrometry, photometry and time series for this identification are described here, along with a discussion of their consequences for the age of 47 Tuc U, the nature of He WDs and their cooling, and the heating effects of an MSP in a close binary.

2. OBSERVATIONS AND ANALYSIS

2.1. Astrometry

We assumed the astrometric coordinate system of the MSPs (based on the JPL DE200 planetary ephemeris; FCL01) as our reference. First, we transferred the *Chandra* coordinate frame onto the radio frame using only the relatively isolated MSPs with accurate *Chandra* positions (six MSPs including 47 Tuc U). We calculated and subtracted the mean positional offsets between the X-ray and radio coordinate systems and found the rms residuals were $0''.136$ and $0''.037$ for RA and Dec respectively (after correcting for small linear correlations between RA and RA error and Dec and Dec error). The total error of $0''.14$ compares favorably with the mean predicted *wavdetect* error, at the relevant count levels and in the absence of background and crowding, of $0''.15$.

We then fixed the *HST* coordinate system, with positions based on the STSDAS program *metric*, onto that of

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Chandra using the X-ray detection of 6 CVs and active binaries found on the WF2 chip of the Gilliland et al. (2000) *HST*/WFPC2 data (this chip contains 4 of the 6 MSPs, including 47 Tuc U, used to perform the radio to *Chandra* astrometry). The rms residuals were found to be 0''.028 and 0''.079, for RA and Dec respectively. Then, assuming the errors are random and dividing by $\sqrt{6}$, the resulting 1σ errors matching X-ray to optical are 0''.011 and 0''.032 for RA and Dec, and for radio to optical are 0''.057 and 0''.049.

Using this astrometry we searched directly for MSP companions in the *HST* images and found an excellent candidate for a companion to 47 Tuc U (hereafter U_{opt}) whose position is given in Table 1. Finding charts for U_{opt} (Fig. 1) show the *U*-band and *V*-band images, plus the 3σ error circle for W11 (the *Chandra* X-ray source corresponding to 47 Tuc U) and the 3σ error ellipse for 47 Tuc U. The offset between W11 and U_{opt} is 0''.055, and between 47 Tuc U and U_{opt} is 0''.10.

2.2. Photometry

Figure 1 shows that U_{opt} is clearly blue, since other stars in the *V* image of comparable brightness to U_{opt} are barely visible in the *U* image. This impression is confirmed by our *V* vs *U* – *V* and *V* vs *V* – *I* color-magnitude diagrams (CMDs) from PSF-fitting photometry shown in Figure 2 (we have transformed from *HST* filters to Johnson-Cousins using Holtzman et al. 1995; see also Table 1). The star U_{opt} (labeled ‘U’; $M_V = 7.47$) is blueward of the main sequence (MS) in both CMDs, where the internal error for U_{opt} is $\lesssim 0.03$ mag for each filter, with absolute errors of ~ 0.05 mag in *V* and *I* and ~ 0.1 mag in *U*, including transformation uncertainties. A likely CV is labeled (‘1’) as are 5 blue stars (circles) confirmed by visual examination to be relatively bright in *U* like U_{opt} . One of these blue stars is probably a CO WD (see Zoccali et al. 2001), two others are variable and likely CO WD-MS binaries and the other two are possibly also binaries. Visual examination showed that the other apparently blue stars, with $V < 22$, are caused by crowding and photometric error, particularly in the crowded portions of the image nearest to the cluster center. Many of the fainter stars with $V > 22$ and $0 \lesssim U - V \lesssim 1$ are bona-fide blue stars, likely to be dominated by MS stars from the SMC (see Zoccali et al. 2001).

The very small number of stars that are blue and detectable in each of *U*, *V* and *I* highlights the unusual nature of U_{opt} and its likely association with 47 Tuc U. With 7 such blue stars the probability (averaged over the whole WF2 image) of detecting one in a circular aperture of 0''.15 radius is only 9×10^{-5} .

2.3. Time Series

The *HST*/WFPC2 data of Gilliland et al. (2000) contain 636 *V*-band and 653 *I*-band 160 s images evenly spread over 8.3 days. Typical rms noise values in fractional intensity (Gilliland et al. 2000) are ~ 0.003 at $V = 17$ and ~ 0.013 at $V = 20$. Since U_{opt} is relatively well isolated, the quality of its *V* and *I* time series, based on its extracted aperture of 0''.34, is excellent. Its rms noise values are 0.021 (*V*) and 0.034 (*I*), or -0.1 and 0.6σ away from the mean rms values for the 666 (*V*) or 551 (*I*) stars within

0.25 mag of U_{opt} , after iteratively removing $> 3\sigma$ outliers.

We then searched for evidence of low amplitude variations in U_{opt} . Lomb-Scargle (Scargle 1982) power spectra of the *V* and *I* time series for 47 Tuc U are shown in the upper panel of Figure 3. This shows a peak in the *V*-band, at $(2.681 \pm 0.07) \times 10^{-5}$ Hz, which is coincident with the orbital period for 47 Tuc U (2.697×10^{-5} Hz) determined from radio observations. Although this peak is not statistically significant in a blind search, only one other peak, when measured out to 0.45 mHz (the ‘average’ Nyquist frequency; Scargle 1982) has a higher signal. No corresponding signal is seen in the *I*-band.

We then carried out a least-squares fit of a sinusoid to the time series, by coordinating the radio ephemeris with the optical and correcting the mid-exposure *HST* times to the barycenter, using the IRAF task *rvcorrect*. We define phase = $[T - (T_{\text{asc}} - P/4)]/P$ (where T is the barycentric time, T_{asc} is the time of ascending node, when the pulsar is moving with maximum velocity away from us, and P is its orbital period) so that when phase = 0.0 the heated hemisphere of U_{opt} is facing towards us, giving maximum light (in a model where U_{opt} is heated by the pulsar wind). The derived period, time of optical maximum (phase = 0) and semi-amplitude for the *V*-band time series are given in Table 1 (*V* phase plots are shown in the lower-left panel of Fig. 3). For the ‘unforced’ solution the period is 0.7σ away from the orbital radio period, and the phase is 1.9σ away from phase zero for the radio observations (as defined above). The amplitude is significant at the 3.4σ level (the significance of this measurement is $> 3.4\sigma$ when the $\sim 1/10$ chance probability of the radio and optical phases aligning is considered). By forcing the period and phase of the sinusoidal variation to equal the radio values (the ‘forced’ solution), an amplitude of 0.0033 ± 0.0012 is derived, significant at the 2.8σ level; a forced fit in the *I*-band yielded 0.0013 ± 0.0018 . Marginal evidence is found for variation in the much more limited (26 images of length 160 s – 900 s) *U*-band data (see Fig. 3).

To test whether this small variation in *V* is intrinsic to U_{opt} rather than a larger variation from a nearby fainter star we examined the power spectra of 3 fainter stars (with $V \gtrsim 22$) lying within $\sim 0''.5$ of U_{opt} . None showed significant variations. We also examined a ‘phase difference’ image derived by adding together images where the phase of U_{opt} is within 0.07 of 1.0 and subtracting similar images for phase values of 0.5 ± 0.07 . This procedure gave a stellar-shaped source coincident, at the 0.5 pixel (0''.05) error level, with U_{opt} , exactly as expected if U_{opt} is the only star varying with the radio period and phase. We therefore conclude we have made a solid detection of variability from U_{opt} at the expected period and phase, confirming it as the 47 Tuc U companion.

3. DISCUSSION

Neutron stars (NSs) in binary radio pulsar systems have average masses of $M_{\text{NS}} = 1.35 \pm 0.05 M_{\odot}$ (Thorsett & Chakrabarty 1999). For 47 Tuc U, considering a NS mass $1.30 M_{\odot}$ and an edge-on orbit (inclination $i = 90^\circ$), we derive from the mass function a minimum mass for U_{opt} of $M_U = 0.120 M_{\odot}$. This 4.3 ms pulsar has an approximate characteristic age of $\tau \sim 2$ Gyr and spin-down luminosity of $\dot{E} \sim 2 \times 10^{34}$ erg s $^{-1}$ (Grindlay et al. 2001, in prepara-

tion). Such recycled pulsars may have accreted significant amounts of mass, and for every additional $0.05 M_{\odot}$ for the NS, M_U 's minimum value increases by $0.003 M_{\odot}$.

We now compare the U, V, I colors of U_{opt} with expectations from H and He WD models to test whether it is a plausible He WD and if so, to estimate T_{eff} , $\log g$, and the mass and age of this star. We focus on comparisons with the models of Serenelli et al. (2001; hereafter SAR01), who conveniently provide broadband color information. They find that for masses ranging from $0.18 M_{\odot}$ to $0.41 M_{\odot}$, diffusion-induced hydrogen-shell flashes take place which deplete the H envelope and cause evolution to proceed relatively quickly, while the He WDs with mass $< 0.18 M_{\odot}$ evolve much more slowly because they retain relatively thick hydrogen envelopes. Althaus, Serenelli, & Benvenuto (2001) and SAR01 show that this dichotomy between low and high mass He WDs removes the discrepancies between MSP characteristic ages and WD cooling ages for several field systems including PSRs J0034–0534, J1012+5307, J1713+0747 and B1855+09.

Figure 2 shows the He WD cooling curves of SAR01 for masses of $0.169 - 0.406 M_{\odot}$. Since U_{opt} lies well to the red of the WD cooling sequence of Bergeron, Wesemael, & Beauchamp (1995) in both CMDs, it is unlikely to be a $\sim 0.55 M_{\odot}$ CO WD. The lowest mass models of SAR01 offer much better agreement, and since U_{opt} falls slightly to the red of the lowest mass sequence we infer that $M_U \lesssim 0.17 M_{\odot}$ (implying $i \gtrsim 45^\circ$). This would mean that 47 Tuc U is similar to the field system PSR J1012+5307, with period = 0.605 d and mass $\sim 0.16 M_{\odot}$ (Callanan, Garnavich, & Koester 1998).

The $0.17 M_{\odot}$ SAR01 model with the same absolute magnitude as U_{opt} has $T_{\text{eff}}=11000$ K, $\log g = 5.6$, luminosity = $0.14 L_{\odot}$, a radius⁵ of $\sim 7.3 \times 10^9$ cm and an age of ~ 0.6 Gyr. This cooling age is somewhat less than the characteristic age estimated by Grindlay et al. (2001, in preparation) and is at the low end of the conservative limits set by FCL01 of $0.4 < \tau < 4.2$ Gyr. Only the lowest mass model of SAR01 remains relatively bright at these significant cooling ages, while all of the higher mass WDs reach much fainter levels ($M_V \sim 12$) at a cooling age of ~ 1 Gyr (see Fig. 2). Our data therefore provides tentative support for the evolutionary calculations of SAR01, in particular for the dichotomy in ages between different mass He WDs. For comparison, the He WD models of Hansen & Phinney (1998) (for all masses) reach $M_I=11.5$ or fainter after 1 Gyr, for a relatively thick hydrogen envelope of $3 \times 10^{-4} M_{\odot}$.

Accretion should have ceased in the 47 Tuc U system, to explain the faint X-ray luminosity (2×10^{30} erg s^{-1} ; Grindlay et al. 2001, in preparation) and the constant, uneclipsed radio emission (FCL01). Using

the Roche-lobe formula from Paczyński (1971) ($r/a = 0.462[(M_U/(M_{\text{NS}} + M_U))]^{1/3}$, where r is the Roche-lobe radius, and a is the binary separation), the WD radius given above (for $M_U = 0.17 M_{\odot}$; $i = 45^\circ$) and the binary separation from Kepler's Third Law, U_{opt} should under-fill its Roche lobe by a factor of ~ 6 . Therefore, as expected, no accretion will be occurring.

Assuming that the MSP radiates its wind isotropically, and that $i = 45^\circ$, then the \dot{E} estimate implies that the pulsar energy intercepted by U_{opt} should be $\sim 7 \times 10^{30}$ erg s^{-1} or $0.013 \times$ the luminosity of U_{opt} (assuming that the spin-down energy is re-radiated as a black-body, we derive a temperature of ~ 5200 K, peaked at $\sim 5600 \text{\AA}$, for the re-radiated emission). Therefore, assuming that only one side of U_{opt} is heated we should see a relative variability amplitude of ~ 0.005 , allowing a factor of 1.4 decrease in possible amplitude because of the inclination. This is only slightly larger than the amplitude of the detected V -band variation, implying a high efficiency factor for re-radiation of the pulsar's wind as optical emission. However, because the variability expected from the effects of heating is small, we infer that the possible (2.3σ) much larger amplitude variation in the U -band is either spurious or evidence for a separate source of emission.

4. SUMMARY AND FOLLOWUP OBSERVATIONS

We have identified the binary pulsar 47 Tuc U with an optically variable blue star with period and phase of maximum light in excellent agreement with that expected from the precise radio ephemeris (FCL01). The companion is likely to be a He white dwarf with $M_U \lesssim 0.17 M_{\odot}$, based on the published models of SAR01.

Although the optical time series photometry reported here is unlikely to be improved upon soon, time resolved spectroscopy with *HST*/STIS of U_{opt} appears promising. The co-added Doppler corrected spectrum could be used to spectroscopically determine T_{eff} and $\log g$, and hence M_U (see e.g. Edmonds et al. 1999). Combining M_U with the radial velocity amplitude of U_{opt} (K_U) and the measured K_{NS} from the radio measurements would give a direct measurement of M_{NS} .

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⁵ The estimated radius is fairly insensitive to the details of the Serenelli et al. (2001) WD models, since T_{eff} can be estimated accurately just from the $V - I$ color (Hansen & Phinney 1998), and the luminosity using only the V magnitude and T_{eff} .

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TABLE 1
POSITIONAL, PHOTOMETRIC AND TIME SERIES INFORMATION FOR 47 TUC U AND ITS OPTICAL COMPANION U_{opt}

RA ^a (J2000)	Dec ^a (J2000)	<i>U</i>	<i>V</i>	<i>I</i>	period(<i>V</i>) (days)	<i>T</i> (phase=0) ^b (MJD)	amp(<i>V</i>) (mag)
00 24 09.8325(5)	−72 03 59.667(3)	20.6(1)	20.91(5)	20.70(5)	0.432(4)	51367.32(2)	0.004(1)

^aCoordinates from Freire et al. (2001)

^bTime of optical maximum (see text)

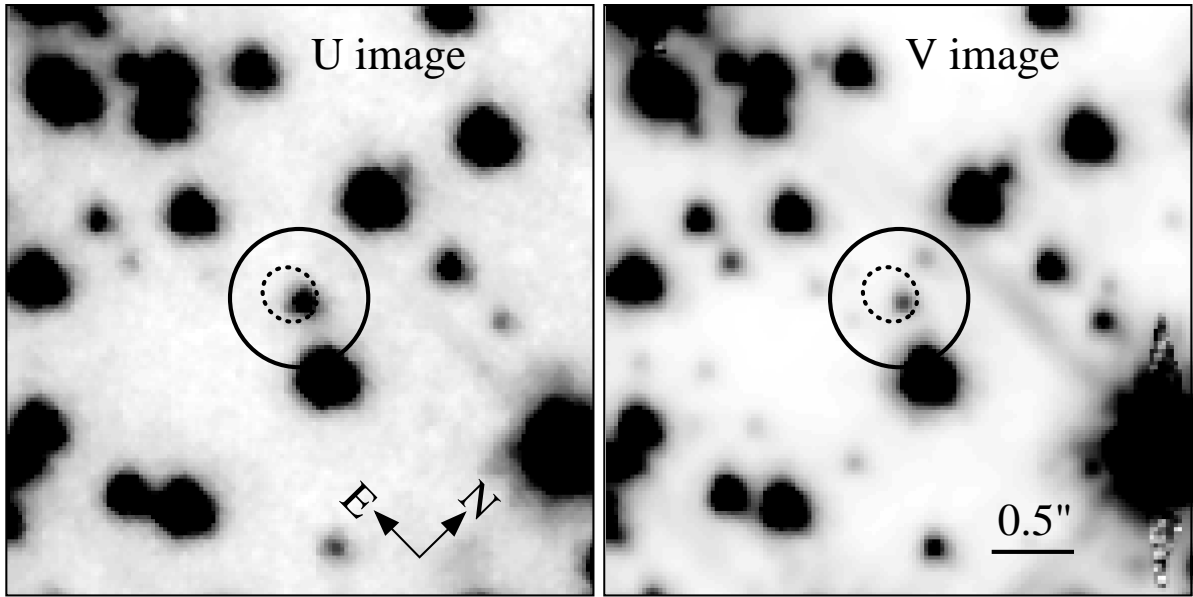


FIG. 1.— Finding chart for 47 Tuc U showing the co-added (over 8.3 d), oversampled images for the U - and V -band. The solid line shows the 3σ error circle (radius = $3 \times 0''.14$) for the X-ray source W11, and the dotted line the 3σ error ellipse for the radio pulsar 47 Tuc U, after accounting for the transformation between radio and optical frames and assuming random errors. The optically detected binary companion to 47 Tuc U (U_{opt}) is near the center of the W11 error circle.

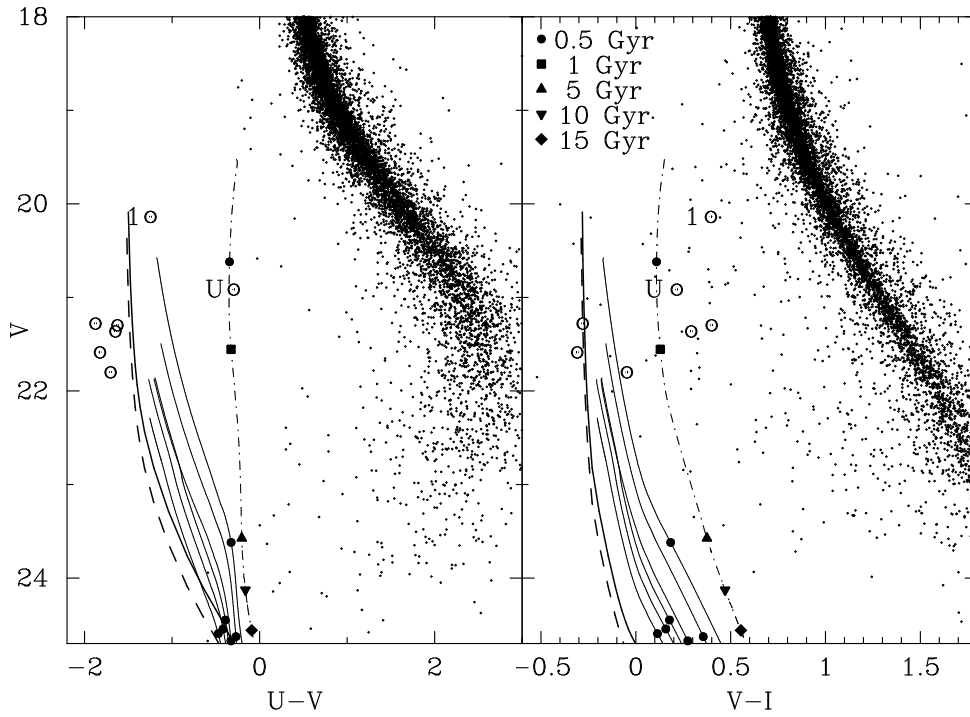


FIG. 2.— V vs $U - V$ and V vs $V - I$ CMDs for the WF2 chip. The 47 Tuc U MSP companion U_{opt} is denoted by ‘U’, a CV by ‘1’ and other blue stars are circled. The position of U_{opt} is slightly redder and brighter than those of the He WDs in NGC 6397 reported in Cool et al. (1998). The thicker lines show Bergeron, Wesemael, & Beauchamp (1995) models for $0.5 M_{\odot}$ (dashed line) and $0.6 M_{\odot}$ (solid line) CO WDs. The thinner lines are SAR01 models, for He WD masses of $0.406, 0.360, 0.327, 0.292, 0.242, 0.196 M_{\odot}$, with mass decreasing towards the red, and $0.169 M_{\odot}$ (dot-dashed line). Cooling ages are as shown. These models have been plotted assuming that $(m - M)_0 = 13.27$, the mean of the 9 distance modulus values reported in Zoccali et al. (2001), $E(B - V) = 0.055$ (Zoccali et al. 2001), $A_U/A_V = 1.51$ and $A_I/A_V = 0.60$ (Holtzman et al. 1995). Using $(m - M)_0 = 13.27$ the 47 Tuc distance is 4.5 kpc.

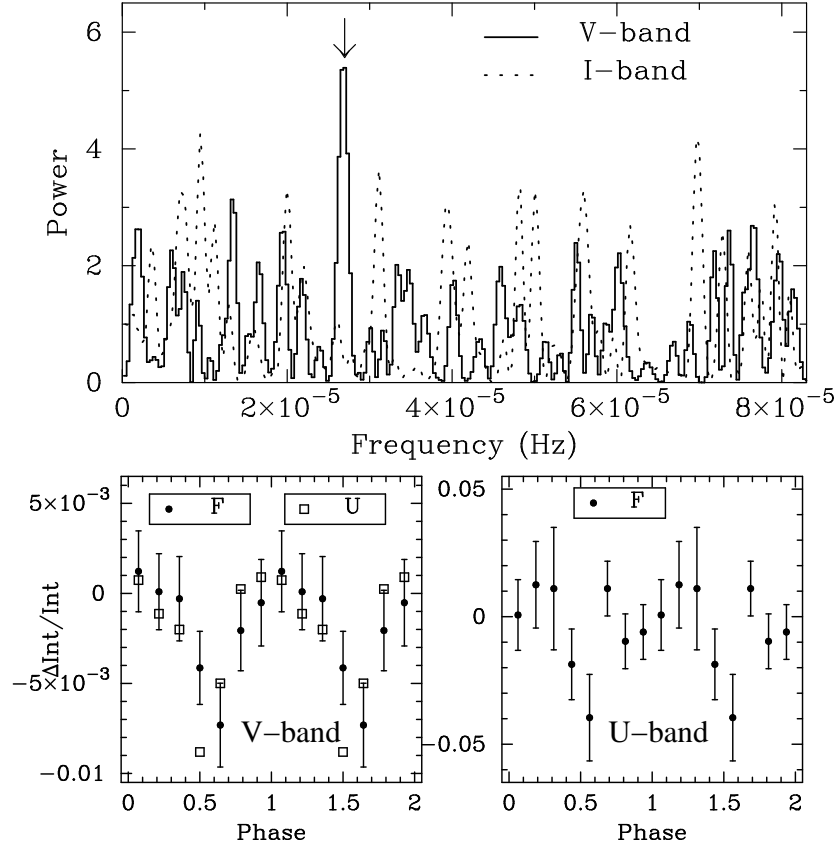


FIG. 3.— Power spectra and phase plots for U_{opt} . The upper panel shows power spectra (V- and I-band, as labeled) for U_{opt} , with power shown in Lomb-Scargle units (Scargle 1982). The binary frequency of 47 Tuc U measured from radio observations is indicated with an arrow. The lower panel shows phase plots for the V- and U-band data for U_{opt} , where fractional intensities are plotted and the errors are from the time series rms values scaled by the square root of the number of points in each bin. ‘F’ denotes the forced fit and ‘U’ the unforced fit (see §2.3 for description). The point near phase 0.5 in the U-band data is formally only significant at the 2.3σ level. No evidence is found for variation in the I-band, and so the phase plot is not shown here.